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A Re-Valuation of the Ancient Science of Harmonics

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Psychology of Music 2003 31: 391
DOI: 10.1177/03057356030314004

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A re-valuation of the ancient science of harmonics

Psychology of Music

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vol 31(4): 391–403
[0305-7356 (200310)
31:4; 391–403; 035785]

LEON CRICKMORE

ABSTRACT Harmonics was the theoretical arithmetic underpinning the tuning of musical instruments in ancient times. It was a numerical science based on ratios of string-length. The ancients believed that the planets circled the heavens in similar mathematical proportions, and that, by analogy, these also corresponded to powers in the human psyche. Harmonics survived as such until the 17th century. Only recently, however, have musicologists made a breakthrough to a more comprehensive understanding of its coherence and cultural significance. This article offers a short re-valuation of harmonics. It seeks to stimulate debate about the relevance of the relationships between number and tone to contemporary thought, and whether an understanding of harmonics has anything to contribute to future interdisciplinary research into the evolution of music and the human mind.

KEYWORDS: *evolution, mathematics, music, Plato, temperament*

Introduction

Harmonics was one of the earliest numerical sciences. It was concerned with the theoretical arithmetic underpinning the tuning of ancient musical instruments. Harmonics probably emerged amongst our stone-age ancestors, matured in ancient India, Babylon and Egypt, and flourished in Greece, which is the source of our earliest surviving records of it. Harmonics continued to maintain its ground until the 17th century, since when it has been overtaken by experimental science and technology.

The frequency of vibration which gives rise to musical pitch varies in inverse proportion to the length of the vibrating string or air-column. There are scientific instruments for measuring frequency of vibration accurately, and modern mathematics can easily handle irrational numbers such as $12\sqrt{2}$, needed to divide the musical octave into 12 equal semitones to form a

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chromatic scale, tuned in the manner which, since the time of Bach, has been known as 'equal temperament'. However, since the ancients were unable to measure frequency accurately, and their mathematics was limited in its capacity to deal with irrational numbers, they defined pitch in terms of ratios of string-length. With the aid of a monochord – an instrument with one string and a movable bridge, designed to keep all other factors constant while string-length alone is varied – they were able to specify musical pitches by means of numbers which represented their magnitude on a given ruler or canon. According to Nicomachus, writing in the 2nd century AD, the Pythagoreans called monochords 'canons' (Levin, 1994: 61). The authors of the ancient texts on harmonics employed ratios with great sophistication. Their science of harmonics was a beautifully proportioned and crafted construct, even if their fascination with correlations between number and tone sometimes led them to confuse acoustical theory with cosmology. Ancient writers recognized three categories of music: cosmic (*musica mundana*), human (*musica humana*) and instrumental (*musica instrumentalis*). The third of these, which for the ancients did not primarily refer to the performance of music by instruments, but rather to the ratios of string-length that relate number to tone, is the focus of this article. Since the development of empirical science and psychology, the first two categories of ancient music rarely feature in modern thinking except as poetic metaphors. Godwin (1986, 1993), however, has compiled two sourcebooks of texts from the literature of human and cosmic music. In the light of the collective impact of these, it seems reasonable to regard such texts as evidence of an ancient intellectual tradition which sought synthesis on the basis of analogies with systems of musical tuning. The earliest surviving treatise on the tuning of the musical scale, *The Division of the Canon*, could date from around the turn of the fourth century BC (see Barbera, 1991). McClain (1976), however, presents a plausible case for a much earlier understanding of harmonics in India, Babylon and Egypt. McClain (1978) demonstrates in detail how Plato used harmonics as a framework for the mathematical and musical allegories in his dialogues.

Ratios and the harmonic series

The main ratios of string-length used in harmonics were called by the ancients 'superparticular' $\left(\frac{n+1}{n}\right)$, e.g. 2:1, 3:2, 4:3 etc. Superparticular ratios correspond to what modern acousticians call the 'harmonic series'. Practical musicians in ancient times would presumably have been familiar with such a series (at least in part) from the scale of the natural trumpet. The three superparticular ratios quoted above are expressed by means of the integers 1, 2, 3, 4, which defined the Pythagorean tetractys. The tetractys was also represented geometrically as a triangle, made up of ten stones or points, from which it is easier to visualize these three superparticular ratios and their reciprocals $\left(\frac{n}{n+1}\right)$ – 1:2, 2:3, 3:4 (Figure 1a). However, the wider mathematical

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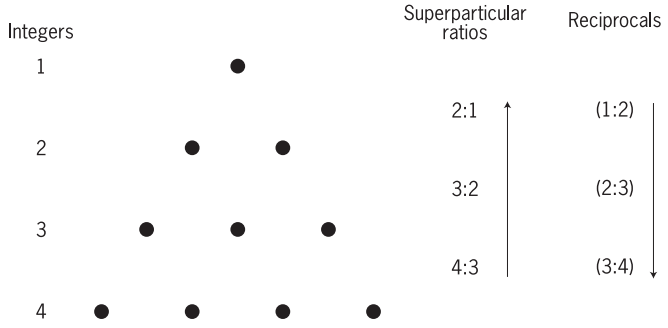

FIGURE 1a *The Pythagorean tetractys.*

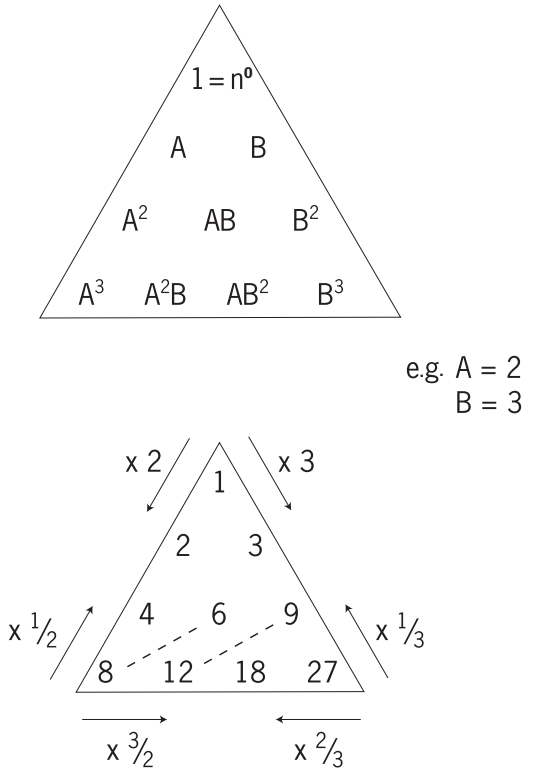

FIGURE 1b *The algebraic implications of the tetractys.*

implications of the tetractys are more likely to be appreciated, if it is expressed in modern algebraic terms (Figure 1b). These implications were understood by the ancients; the algebraic notation alone is modern.

Reciprocity was a fundamental concept in harmonics. In mathematics, the reciprocal of a number is one divided by that number (1/n). In music, it

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simply means the measurement of intervals in an opposite direction, for any ratio can be sung in either direction – up or down. But this can become a serious source of confusion in any historical discussion of harmonics. Modern musicians, accustomed to thinking in terms of frequency increasing by given ratios, initially conceive of musical scales as *rising* (2:1 signifies the octave above). Ancient musicians, however, thought first in terms of increasing string-length and conceived their scales initially as *falling* (2:1 signified the octave below).

Figure 2 summarizes the argument so far. It shows the first six terms of the modern harmonic series, both falling and rising; expressed as superparticular ratios and as their reciprocals; realized musically both by string-length and by frequency. The particular pitches used for the musical notation in this and subsequent figures have been chosen for convenience of presentation only. They are arbitrary and could, of course, have been standardized.

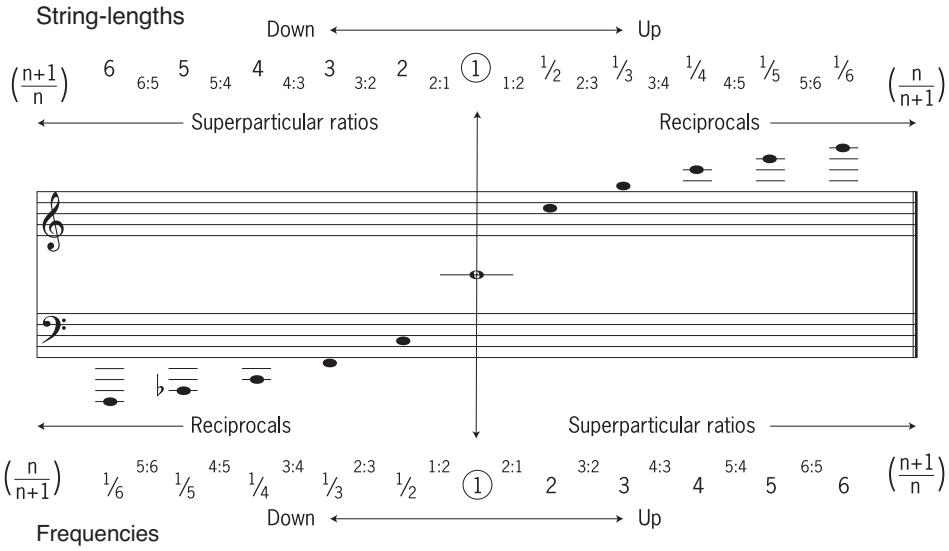
String-lengths
Down
Up
(n+1/n) 6 6:5 5 5:4 4 4:3 3 3:2 2 2:1 1 1:2 1/2 2:3 1/3 3:4 1/4 4:5 1/5 5:6 1/6 (n/n+1)
Superparticular ratios
Reciprocals
Reciprocals
Superparticular ratios
(n/n+1) 1/6 5:6 1/5 4:5 1/4 3:4 1/3 2:3 1/2 1:2 1 2:1 2 3:2 3 4:3 4 5:4 5 6:5 6 (n+1/n)
Down
Up
Frequencies

FIGURE 2 *The first six terms of the harmonic series with their ratios.*

The musical tetractys

From Figure 2 it can be seen that the first superparticular ratio (2:1) generates the interval of the octave (diapason); the second (3:2), the fifth (diapente); and the third (4:3), the fourth (diatessaron). Modern musicians refer to these degrees of the scale as the tonic, dominant and sub-dominant, respectively. Placed in descending sequence in the order tonic, dominant, subdominant and tonic octave, they form an ancient pattern, the invention of which is usually attributed to Pythagoras, though its origin was probably much earlier. This pattern is now generally known as the 'musical tetractys'

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or 'musical proportion'. Each musical scale (mode) in ancient Greece contained the four notes of the musical proportion as 'fixed' tones, arranged in two tetrachords (fourths) with a whole tone (9:8, i.e. 3:2 ÷ 4:3 = 9:8) in between. The space within each of the tetrachords was then filled out by two 'variable tones'. According to Pythagorean practice, the two tetrachords must be strictly symmetrical, with their tones defined by integers. Figure 3 illustrates the musical tetractys, its internal relationships and an algebraic expression of the arithmetic by which the note values were calculated.

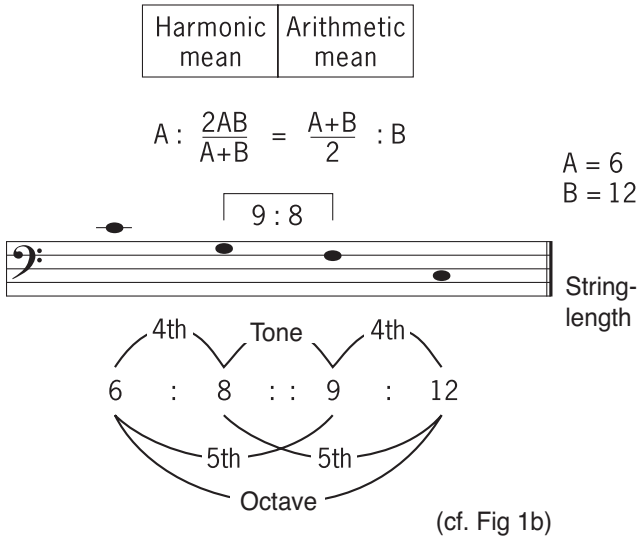

FIGURE 3 *The musical tetractys.*

Plato's World Soul: the Dorian and Phrygian modes in Pythagorean tuning

In his dialogue *Timaeus* (34–37), Plato describes the making of the 'World Soul'. It is to be generated from the prime numbers 2 and 3, by two interlocking geometrical progressions: 1, 2, 4, 8 and 1, 3, 9, 27. In a note to his translation of the *Timaeus*, Lee (1977[1965]: 48) adds that Plato now treats these progressions 'as if they defined a musical scale'. It is a pity that Lee did not pursue the matter to identify this scale. Between each pair of terms, their arithmetic and harmonic means are now inserted: 3/2 and 4/3 (see Figure 3). The intervals of a fourth (4/3) are then filled by two whole tones (9/8), leaving over a remainder – not a superparticular ratio – with the proportion 256:243, i.e. 4/3 ÷ (9/8 × 9/8), or 4/3 ÷ 81/64 = 256/243. This has to serve as a semitone, although it is actually smaller than half a tone. The smallest integers capable of defining the first octave of the World Soul are 384–768. When the calculations have been made, the first octave of the

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World Soul scale will be recognized by musicians as the ancient Greek *Dorian* mode; while the octave 432–864 (items 2–9 in the series) constitutes the *Phrygian* mode. In the *Republic* (398–99c, see Bloom, 1968), Plato limits the modes to be permitted in his model cities to these very two. Modern musicians refer to pitches defined by ratios generated by 2 and 3 only as Pythagorean tuning. The first octave and a tone of the scale defined by the World Soul numbers are shown in Figure 4.

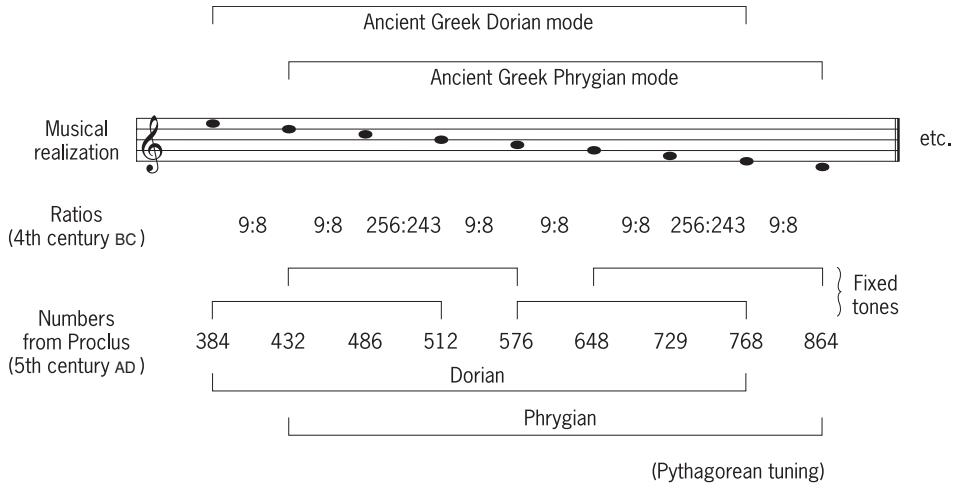

FIGURE 4 *Plato's World Soul.*

The octave 432–864 defines the ancient Greek Phrygian mode in the smallest integers possible. However, the multiplication or division by two of a tone-number simply lowers or raises it by an octave, without changing the letter-name by which the pitch is identified. For instance, 864 can be considered functionally equivalent to 27 (3^3), i.e. $864 \div 2^5$. American musicologists have coined the phrase 'octave equivalence' for this. Indeed, the Phrygian scale in its entirety is therefore implied in the cube of 3. For, musically, starting, for instance from base D, 1:3:9:27 means D, A, E, B, a series of fifths in an upward direction; and D, G, C, F, similarly downwards. Given octave equivalence, these named notes can be rearranged to form the ancient Greek Phrygian mode (see Figure 4).

Another significant feature of this tuning of the Phrygian mode is that its ratios remain invariant under reciprocation: ➔ 9:8, 256:243, 9:8, 9:8, 9:8, 256:243, 9:8 ←. Thus the numbers 432, 486, 512, 648, 729, 768, 864 (see Figure 4) function simultaneously as ratios of frequency and of string-length to define the same scale ascending and descending. Perhaps it was on account of the convenience of its symmetry in reciprocation that this ancient Greek Phrygian scale – represented by the white notes of the piano in the octave D to D – became the first of the eight Church Modes (*protus authenticus*

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or *primus tonus*). To add to the confusion, from about the end of the eighth century AD, some ancient writers label this scale *Modus Dorius*. In consequence, if asked to explain the Dorian mode, modern musicians will sometimes simply describe it as the white notes D–D on a keyboard, failing to distinguish between the mediaeval Dorian and the ancient Greek Dorian modes. The Dorian mode of the ancient Greeks should be described, equivalently, as the white-note octave E–E, descending (see Figure 4). As already noted, the ancient Greeks viewed their scales, initially, as descending, i.e. corresponding to increasing string-length. It is particularly important to bear this in mind when considering the Dorian mode, for in Pythagorean tuning, the Dorian mode, unlike the Phrygian, differs under reciprocation. The reciprocal of the ancient Greek Dorian mode is our modern major scale (Figure 5).

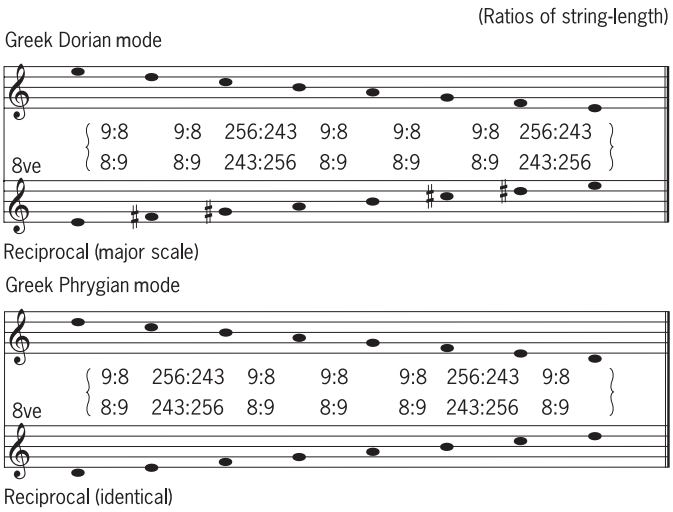
(Ratios of string-length)
Greek Dorian mode
8ve
9:8 9:8 256:243 9:8 9:8 9:8 256:243
8:9 8:9 243:256 8:9 8:9 8:9 243:256
Reciprocal (major scale)
Greek Phrygian mode
8ve
9:8 256:243 9:8 9:8 9:8 256:243 9:8
8:9 243:256 8:9 8:9 8:9 243:256 8:9
Reciprocal (identical)

FIGURE 5 *The ancient Greek Dorian and Phrygian modes with their reciprocals.*

Plato's *Timaeus* and its World Soul scale never sank entirely into oblivion during the dark and middle ages on account of a Latin translation of its first part by Calcidius. Then, from the ninth century, the *De Institutione Musica* of Boethius – composed early in the 6th century and containing translations and paraphrases of passages from the *Sectio Canonis*, works by Nicomachus and Ptolemy's *Harmonica* – ensured that the science of harmonics was transmitted through to the renaissance and beyond (Bower, 1989).

Just tuning

The ancient Greek Dorian mode can also be defined by smaller integers than the 384–768 shown in Figure 4. To achieve this, the prime number 5 has to be used as a generator, in addition to 2 and 3. Just as Pythagorean tuning was

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generated from interlocking geometrical progressions from 2 and 3, so the new tuning system is generated by 2, 3 and 5. Modern musicians call such a system *Just tuning* (Figure 6). Figure 7 shows the Greek Dorian mode and its reciprocal in Just tuning. This particular tuning was known as Ptolemy's *Diatonic Syntonon* (2nd century AD).

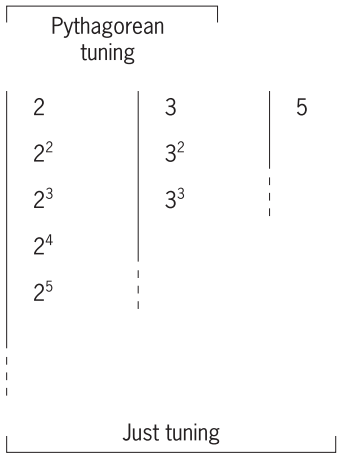

FIGURE 6 *The arithmetical basis for Pythagorean and Just tuning.*

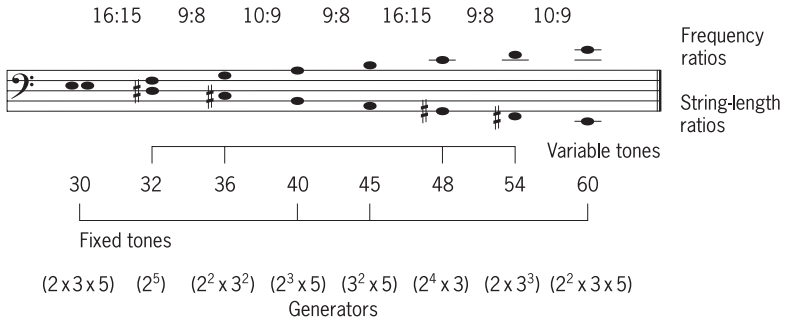
16:15 9:8 10:9 9:8 16:15 9:8 10:9
Frequency ratios
String-length ratios
Variable tones
30 32 36 40 45 48 54 60
Fixed tones
(2 x 3 x 5) (2^5) (2^2 x 3^2) (2^3 x 5) (3^2 x 5) (2^4 x 3) (2 x 3^3) (2^2 x 3 x 5)
Generators

FIGURE 7 *Ptolemy's Diatonic Syntonon.*

To express this tuning in the smallest integer ratios of string-length requires the octave 72–144 (namely, 72, 80, 90, 96, 108, 120, 135, 144). Both these tunings involve the use of 10:9 as well as 9:8 to define a whole tone. Major and minor thirds are 5:4 and 6:5, respectively, as in the harmonic series (Figure 2). Plato's friend, Archytas, went on to experiment with a whole tone in the ratio 8:7. This entailed the introduction of yet another prime number (7) as a generator (namely, 9:8, 8:7, 28:27, 9:8, 9:8, 8:7, 28:27). But such a tuning proved to be of little help to practical musicians: its 'semitone' (28:27) was far too small. To the present author, one significant point about Archytas's use of the septimal tone ratio for his diatonic tuning,

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is that his scale can be accommodated in the octave 5040–10080. And Plato proposes 5040 – one of the very few specific numbers mentioned in his mathematical/musical passages – as a convenient limit for the number of citizens in his model city of Magnesia (*Laws*, 737 and 771, see Saunders, 1970).

Plato's musical allegories

Plato's dialogues abound in references to music and musical/mathematical allegories. For centuries these mathematical constructions have defied attempts by Platonists to explain them adequately. Only in the last 30 years or so have scholars in America (e.g. McClain, 1976, 1978; Godwin, 1993; Levin, 1994) made a breakthrough, though their achievement has not yet been absorbed into modern classical scholarship. One notable exception is Solomon (2000). Plato's description of his model city of Magnesia is one of the most sophisticated of these musical allegories. McClain (1978: 97–115) has interpreted it in detail and in a manner likely to be considered convincing by most thinking musicians. Moreover, it is an interpretation which can be applied consistently and effectively throughout Plato's later dialogues. Plato seems so determined that everything in Magnesia should be limited and regulated by numbers that some commentators have felt obliged to label him a fascist. McClain's view is milder; he suggests that Plato was simply a musical humorist. McClain analyses Magnesia in terms of a tuning system like the one devised by Archytas, generated from the primes 2, 3, 5 and 7, with 5040 ($2^4 \times 3^2 \times 5 \times 7$, or 7!) as its limiting index.

Another number to which Plato makes explicit reference is 729 (*Republic*, 587–8, see Bloom, 1968). This, Plato claims, is the number of times by which the philosopher king lives more pleasantly than a tyrant. Often assumed to be no more than a rhetorical flourish or poetic exaggeration, the choice of 729 will quickly be recognized by students of harmonics as particularly apt. Assuming octave equivalence, powers of 3 generate a series of perfect fifths, $729 = 3^6$, and produces the tritone (e.g. F to B), an interval shunned by mediaeval musicians as *diabolus in musica* (the devil in music). Thus, by his choice of 729, Plato is identifying the life of a tyrant with the worst possible dissonance known in the musical system of his time. In fact, this kind of harmonic metaphor pervades the whole of Plato's *Republic* (see Bloom, 1968): moral virtue is a harmony in the soul; social justice is a harmony between rulers, guardians and workers. Add to the dissonant tritone, generated by six rising fifths, its reciprocal, produced by six falling fifths, and one comes face to face with that infamous discrepancy known as the Pythagorean comma: the difference between seven octaves (2^7) and twelve fifths $(3/2)^{12} = 3^{12}/2^{19} = 531441{:}524288$ – 'a prodigious calculation' (*Republic*, 587e, see Bloom, 1968). Musically, the Pythagorean comma can be conceived as the difference between, for example, B and C flat. Figure 8 illustrates this crucial flaw intrin-

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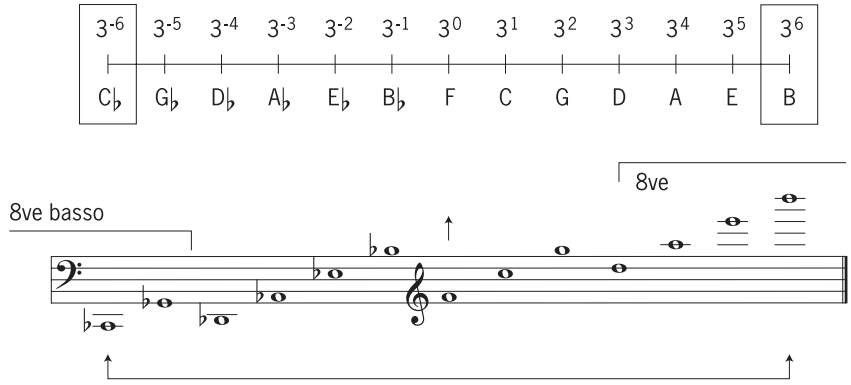

FIGURE 8 *The Pythagorean comma.*

sic to Pythagorean tuning, exacerbated by Just tuning, and remedied only by tuning in Equal Temperament (e.g. B = C flat).

Discussion

Since the 17th century, academic interest in harmonics has tended to be restricted to specialists in acoustics and mathematics. It may now be timely, therefore, to widen the debate to embrace a number of other fields of contemporary knowledge, and to speculate whether harmonics could have a contribution to make to future interdisciplinary research into the evolution of music and the human mind.

In his introduction to McClain (1976), Professor Siegmund Levarie describes this book as 'an intellectual breakthrough of the utmost significance'. But he also recognizes realistically that the author's interdisciplinary approach is unlikely to earn the immediate support of academic experts 'who have become too specialized to view the whole rather than the detail'. McClain (1978) applies his findings to the specific field of Plato's dialogues. Building on the work of Brumbaugh (1954), who had examined every reference to mathematics in Plato, McClain analyses Plato's references to music in the light of harmonics, and attempts to reconstruct the actual numbers and number sets underlying Plato's musical and mathematical allegories. However, the comments on music in the notes of most modern translations of Plato still remain disappointingly unenlightening. One can only speculate over the reasons for this. Has McClain's work been judged and found wanting, sidelined by prejudice, or simply escaped notice? In so far as McClain is right in believing that harmonics was a protoscience, governing not only the musical tuning systems but also the astronomy, calendars, temple construction and myths of several ancient cultures, then ignorance of it, or indiffer-

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ence to it, can only serve as an obstacle to the advancement of research into the evolution of music and the human mind.

The relevance of harmonics to three groups of professionals whose work is of particular interest to readers of *Psychology of Music* warrants specific comment.

(1) PERFORMERS

During the last 50 years, the revival of interest in early music and its authentic performance on period instruments has given rise to the rediscovery, study and practical use of a range of historic tunings. For performers, however, the theoretical side of harmonics is always subordinate to musical instinct. The exact tunings they use (especially singers and string players) are determined by their ears rather than by mathematical calculation. To pitch a note with the voice or to tune an instrument is as much an art as a science. This has probably always been so. Although Plato, an idealist, insisted that tuning theory should be studied exclusively in mathematical terms, Aristoxenus, Aristotle's pupil, known as 'the musician', held that the final arbiter must be the ear.

(2) MUSIC PSYCHOLOGISTS

The ethnomusicologist, Elizabeth Tolbert (2001) and music psychologist, Ian Cross (2001) discuss various theories of the evolution of music and the human mind. Both authors make comparisons between the evolution of music and that of language, but neither refers explicitly to the relationship between tone and number, or to the evolution of mathematics. Cross, however, reflecting on the archaeological evidence for musical behaviours in Upper Palaeolithic times, reports the existence of flint tools capable of producing 'extraordinarily clearly pitched and resonant notes' (2001: 101). Questions such as whether further study of the tuning of these and other lithophones and ancient auloi might provide some indication of how far back in time the musical tetractys can be traced, or how early superparticular ratios were used in musical tuning, require continuing research. Such investigation is likely to call for the expertise of historians of mathematics and science as well as archaeologists. Since the human ear is the only sense organ which recognizes cyclic repetition such as the musical octave, it seems plausible that music may have played a more significant part than is generally realized in the evolution of the human mind.

(3) MUSIC EDUCATORS

Music in the National Curriculum in England (HMSO, 1992), the original specification for music as a foundation subject at Key Stages 1–3, comprises two Attainment Targets: Performing and composing; Listening and appraising. Those responsible for devising this music curriculum might be puzzled, if not irritated, by the following comment from Boethius (see Bower, 1989: 50): 'How much nobler, then, is the study of music as a rational discipline than as

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composition and performance.' There is, of course, no necessary correspondence between the ancient and modern concepts of performers, composers and listeners. In every age, good instrumental practice combines manual skills and musical judgement.

Appendix IV of McClain (1978, cf. McClain, 1970) describes how to tune a monochord with minimum arithmetic complexity by folding a strip of paper of exactly the same length as the sounding portion of the string. There follow exercises to tune scales in Pythagorean and Just tuning and in Equal Temperament. An imaginative team of teachers might construct a monochord and develop a project from this material. The ear's problems could then be demonstrated to the eye. Pupils might experience how musical temperament is always a compromise between conflicting claims, and achieve a greater insight into both music and mathematics than they would from the teaching of each of these disciplines separately. For Plato, education in music – by which he meant harmonics – was 'most sovereign' (*Republic*, 401d, see Bloom, 1968).

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